MULTIWAVELENGTH LASER PROPAGATION STUDY--III

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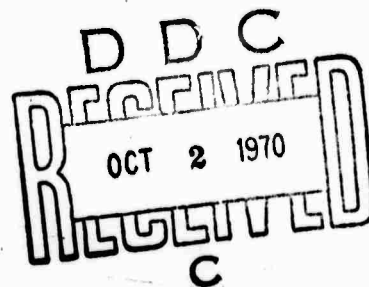for Study and Research
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SUMMARY

This report reviews efforts during the first quarterly period
of Phase III of a comprehensive study of multiwavelength laser scintil-
lations due to atmospheric turbulence. As outlined in the Phase II
Interim Final Report, we are now concentrating on obtaining a large
quantity of experimental data by means of repeated "standard runs"
which include the determination of all pertinent properties of multiwave-
length amplitude scintillations and turbulent structure. During the
period of this report, we have primarily operated under highly saturated
conditions, and we are currently operating under weaker turbulence condi-
tions. The results of these runs will be presented in the next report.

During the high turbulence conditions of the summer months, the
spectrum of turbulence has been found to agree with the "5/3 law" with
the existence of a well-defined inner scale. Also, scintillations have
been strong at the 10.6 micron wavelength, where the transverse amplitude
correlation length has been observed to be smaller than for weaker
turbulence conditions. This suggests the possibility of improved aperture
averaging at this important wavelength.

The intermittency or spiking of turbulent temperature fluctuations has
been found to be a manifestation of the near log normality of the distribu-
tion of the absolute value of those fluctuations. The ramifications of
this result are discussed.

CONTENTS

I. Introduction

This report reviews efforts during the first quarterly period of Phase III of a comprehensive study of multiwavelength laser scintillations due to atmospheric turbulence. The reader is referred to preceeding reports for a detailed description of the program goals and methods.

II. Experiments During the First Quarter

As outlined in the Phase II Interim Final Report, we are now concentrating on obtaining a large quantity of experimental data by means of repeated "standard runs" which include the determination of all pertinent properties of multiwavelength amplitude scintillations and turbulent structure. During the preceeding quarter, we have primarily operated under highly saturated conditions, taking advantage of clear summer days. We are currently operating under non-saturated conditions, and will then extend the standard runs to neutral and inverted conditions.

The results of these runs are largely substantiating the tentative conclusions expressed in the preceeding report. A complete review of the results will be given in the next report, and in a forthcoming paper.

III. New Aspects

A. Miscellaneous Observations

Operation during the summer months under very high turbulence conditions has revealed some new phenomena. The spectrum of turbulence[1] has been found to agree with the "5/3 law" much more consistently than previously reported. However, the existence of a well-defined inner scale on the order of 1 cm is repeatedly verified through these spectral measurements.

Over our approximately one mile path length, log amplitude variances at the 10.6 micron laser wavelength have been typically 0.25, which implies

that CO_2 laser scintillations may be readily saturated over a somewhat longer, horizontal path. Also, under these conditions the transverse amplitude correlation length at 10.6 microns has been smaller than theoretically predicted, and has been similar to that at 4880Å. This predicts that aperture-averaging of saturated scintillations at 10.6 microns may take place with smaller receivers than generally realized.

B. Log Normal Temperature Fluctuations

An important new aspect involves the statistics of the turbulence temperature fluctuations. It was recently pointed out to the author[*] that certain atmospheric physicists in Russia[2,3] and the United States[4,5] have been predicting and partially verifying the log normal character of ΔT, where ΔT refers to the differential temperature fluctuations between two microprobes separated by a distance well within the inertial subrange. Specifically, the quantities $|\Delta T|$ and $(\Delta T)^2$ are described as being more or less log normal over a large probability range, excluding the region in which ΔT crosses zero. These investigators relate the log normality to fluctuations in the rate of turbulent energy dissipation, and hence to the inherent intermittency of the small scale turbulence. They also predict a slight reduction of the exponent in the "5/3 law".

We have experimentally determined the probability distribution of the logarithm of $(\Delta T)^2$, as shown in Figure 1. On each of several occasions, the distribution was substantially log normal. This explains the "spiking" character of temperature fluctuations and the pronounced tail in the distribution of ΔT itself. Hence, the slope of the central portion of the ΔT distribution (on gaussian probability paper) is seen to have no fundamental significance, and has been discarded as a measure of the strength of turbulence.

This log normality of temperature (and velocity) fluctuations explains the quasi-discrete or modulated envelope of ΔT as described by Lawrence

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[*]The author is indebted to P. J. Titterton of Sylvania Electronics Systems, Inc., Mt. View, Calif., for bringing this to his attention.

and co-workers.[6] It should be reiterated that the log normality is
not inconsistent with a Kolmogorov or inertial subrange turbulence
spectrum,[1] and we have in fact repeatedly verified that the spectrum
under high-turbulence conditions does have the Kolmogorov slope down
to the inner scale. As far as amplitude scintillations are concerned,
the important region of the optical filter function[7] is entirely confined
to the verified spectral region, and any large-scale thermal intermittencies
which may accompany the "spiking" of $\triangle T$ are not relevant.

C. An Important Problem

We are thus left with an important dilemma. The turbulence spectrum
often fits the Kolmogorov model over the pertinent spatial frequencies,
thereby validating the basis of most theoretical treatments of the problem.
The parameter C_n^2 may thus be deduced from $\overline{(\triangle T)^2}$, which is directly
measured with a mean-square circuit. (It may also be determined from the
slope of Figure 1, providing that $\overline{|\triangle T|}$ is also known.)

However, as discussed in earlier reports and by other investigators,[8]
C_n^2 as determined in this manner is too large when compared to non-saturated
log amplitude variances. In the present experiments, the short-path
$6328\overset{\circ}{A}$ scintillations are definitely non-saturated, and the long-path
10.6 micron scintillations are probably likewise. Yet in every case,
the log amplitude variances predicted from $C_n^2 \sim \overline{(\triangle T)^2}$ are from typically
two to four times higher than the experimentally-observed values.

The laser transmitters utilized in these experiments represent virtual
point sources, and the usual Rytov expression for a spherical wave is
utilized for the prediction of log amplitude variance:[9]

$$\sigma^2 = 0.124 \; C_n^2 \; k^{7/6} \; L^{11/6} \; . \tag{1}$$

Since the statistics of the thermal fluctuations do not enter into the
derivation of this expression, the log normality (rather than normality)
of $\triangle T$ should not be a factor. Nevertheless, it seems that the spiking
in $\triangle T$ leads to $\overline{(\triangle T)^2}$ values which are higher than those for the true
"optical strength of turbulence." In fact, many published "saturation"
curves,[10] which are plots of experimental σ^2 vs. theoretical σ^2 (Eq. 1)

may have their horizontal axes stretched due to this effect.

One assumption that enters the derivation of Eq. 1 and related expressions is that of "local homogeneity." This refers to the use of limited structure-function arguments (separations), and the requirement that C_n^2 be substantially constant over scale lengths on the order of the outer scale.[1] However, reference to a time record of the fluctuations shows that the ΔT spikes often persist very briefly, corresponding to a high-turbulence region of only centimeters in size; such regions may furthermore be separated by much longer "quiescent" regions. Hence, the assumption of local homogeneity may in some sense be inapplicable due to the high intermittent nature of the turbulence.

To illustrate how such a situation may apply, we may consider the following extreme case. Suppose that there exists an optical path which is instantaneously quiescent over all but a region near the receiver (L'). One must apply the geometrical-optics expression, involving the inner scale, to obtain the log amplitude variance:[1]

$$\ell^2 \sim c_n'^2 \ L'^3 \ell_0^{-7/3} \ , \qquad (2)$$

where $C_n'^2$ represents the actual refractive index constant in the highly turbulent region. This assumes that $\ell_0 > \sqrt{\lambda L}$, which is often the case for e.g. 200 meter segments of path length. Now, the true variance as obtained from Eq. (2) will be much smaller than that obtained from Eq. (1), where C_n^2 is taken as the path-averaged (or time-averaged) value.

Physically, the above argument relates to the fact that short regions of turbulence are optically less weighted than are long regions. For instance, suppose that an otherwise quiet path of length L contains a turbulent plume of length KL, where $K \ll 1$. Then, referring to Eqs. (1) and (2), the refractive index structure constant within the plume is given by

$$c_n'^2 = c_n^2/K \ , \qquad (3)$$

where C_n^2 is again the average value. If we then take the ratio of the

variances of Eqs. (2) and (1), we have

$$\frac{\sigma'^2}{\sigma^2} \sim \frac{K^2 L^{7/6} \lambda^{7/6}}{\ell_0^{7/3}} \quad . \tag{4}$$

This ratio is the true variance divided by the predicted value based on an average C_n^2, and becomes arbitrarily small as K decreases to zero.

Since this situation repeats many times over a real path, this mechanism may provide a clue to the overly-high values of C_n^2 which are obtained thermally.

D. Inner Scale

The direct measurements of the turbulence spectrum have often indicated an inner scale such that $\ell_0 \gtrsim \sqrt{\lambda L}$ for the short-path, 6328Å system. For $\ell_0 > \sqrt{\lambda L}$, the theoretical prediction for a point source is[11]

$$\sigma^2 = 0.32 \ C_n^2 L^3 \ell_0^{-7/3} . \tag{5}$$

If we set Eq. (5) equal to Eq. (1), we obtain the breakpoint or critical value of ℓ_0 as

$$\ell_{0 \ cr}^2 = 0.36 \ L \ \lambda \quad . \tag{6}$$

Hence, for ℓ_0 equal to 1 cm, the reduction in the variance from that predicted by Eq. (1) is approximately a factor of three for our case.

Since the value of the inner scale as determined from the thermal spectral measurements involves uncertainties due to the wind fluctuations, the determination of C_n^2 from Eq. (5) will be likewise uncertain. An alternative use of (5) is to utilize C_n^2 as obtained thermally or at another (non-saturated) wavelength, and independently deduce the inner scale value as

$$\ell_0^{7/3} = \frac{0.32 \ C_n^2 \ L^3}{\sigma^2} \quad . \tag{7}$$

These considerations have been added to the interpretation of data from the "standard runs".

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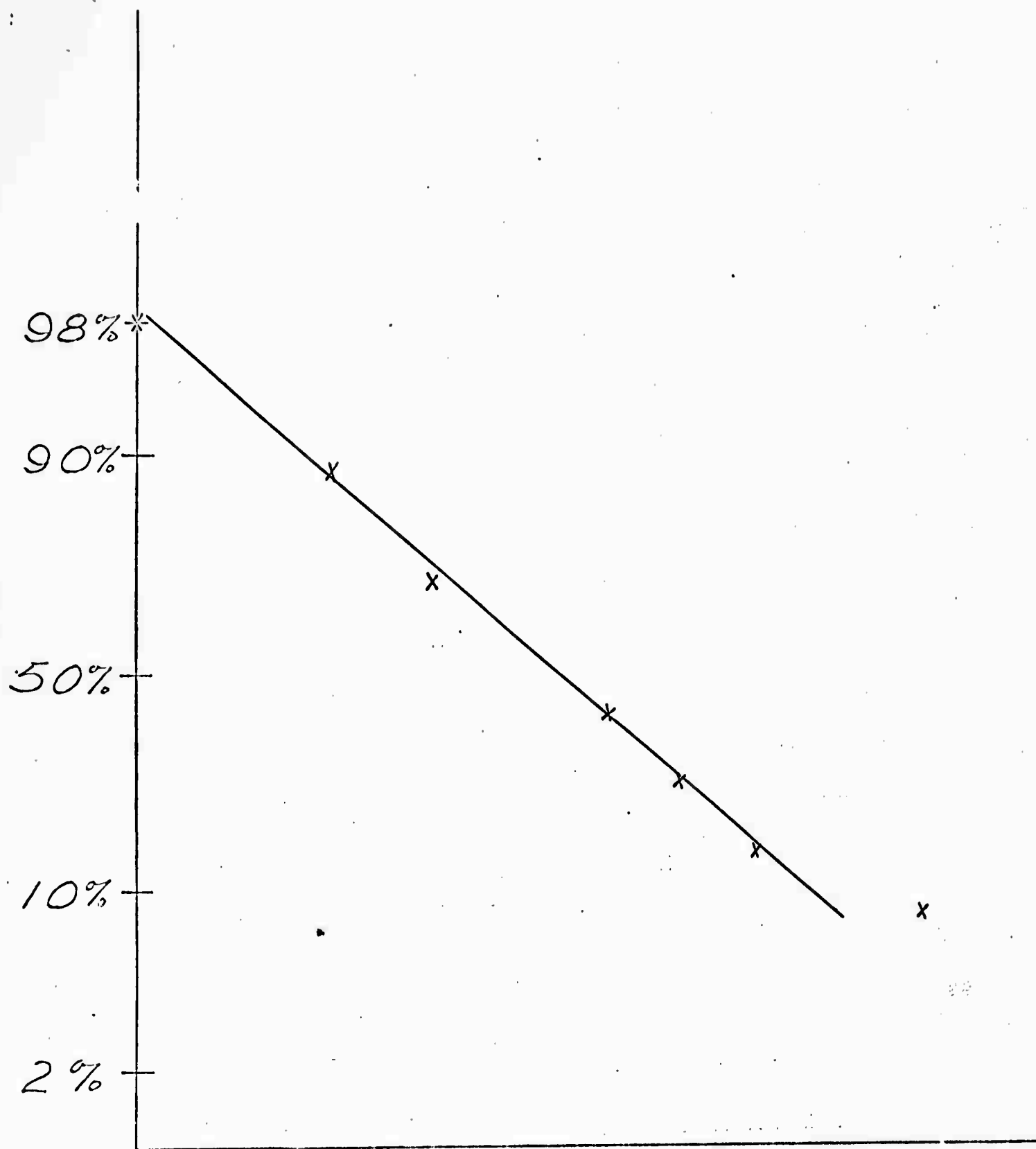
Figure 1

Probability Distribution of $\log (\Delta T)^2$

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13. ABSTRACT

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